EUROfusion

Fusion, Neutronics and Nuclear Data

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KIT IJS UNED CCFE PSI IFIN-HH TU WIEN

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Outline

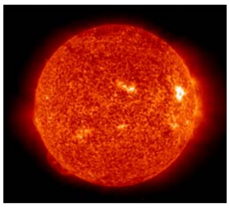
- **What is fusion ?**
- **EU fusion roadmap**
- **Neutronics simulations in fusion technology**
- **Nuclear data for fusion applications**
  - Transport simulations
  - Activation & transmutation
- **Nuclear data in the PPPT programme**
- **Summary**

Addendum:

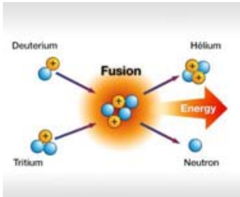
– **DEMO nuclear analyses - examples**

What is fusion?

Bringing the power of the Sun to Earth

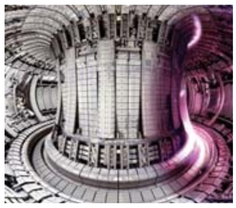


- Fusion is the process that powers the stars



d + t ⇒ α + n + 17.58 MeV

- Light nuclei fuse at very high temperatures
- Release large amounts of energy



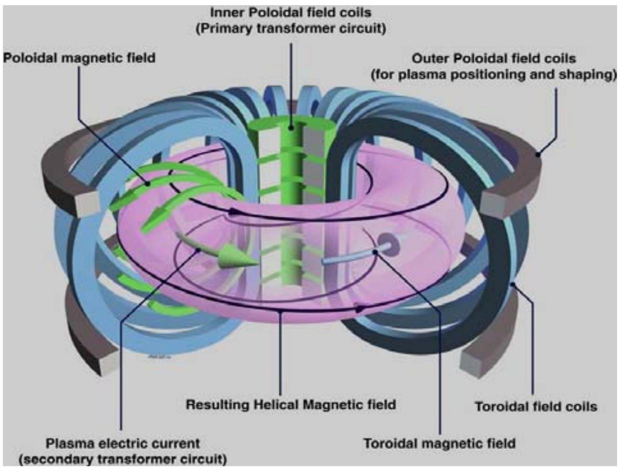
- Need temperatures of >150,000,000° C

⇒ Plasma

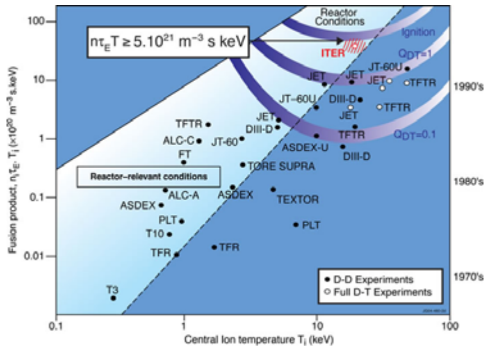
What is fusion?

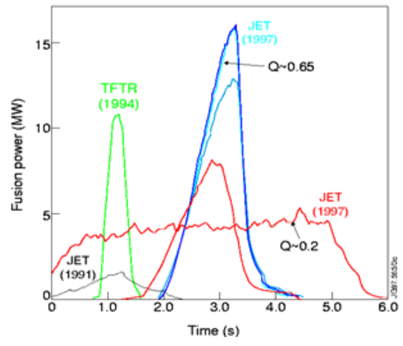
- Magnetic fields to confine the plasma
- Tokamak most successful configuration
- Several experiments in EU and the world

Tokamak



What is fusion?





- Steady physics and engineering progress towards reactor conditions (sustained Q = power in/power out > 1) by increasing plasma density, temperature and confinement time

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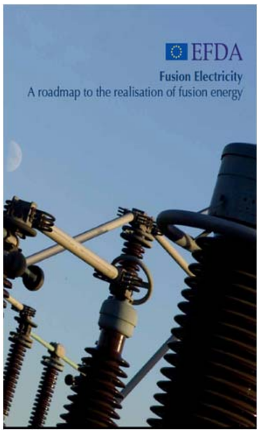
European Fusion Roadmap

Goal: *Realization of fusion as energy source for electricity by 2050 (Fusion Power Plant, FPP, to provide electricity to the grid)*

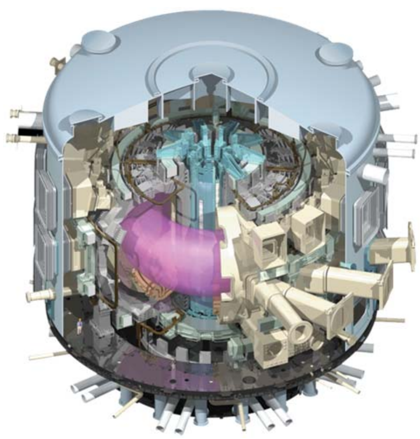
- Included in Strategic Energy Technology Plan ("SET-Plan").
- "Horizon 2020"
  - Implementation of Fusion Roadmap
  - Aim: Achieve all know-how required to start construction of DEMO around 2030
- Requires **three major facilities**:
  - **ITER – key facility for "next step"**
  - **Dedicated "elementary" neutron source for material development (2025)**
  - **"Early" DEMO (2030-35)**



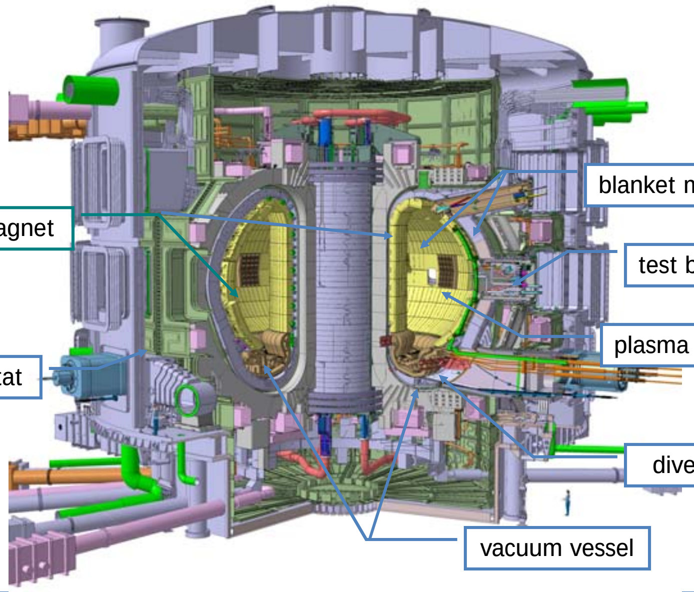
ITER – The way to fusion

Demonstrate that fusion is a viable source of energy

- Test and integrate key fusion technologies for future reactors
- On a larger scale than in present experiments
- 10 times as much power out (500 MW) as power in (Q=10)
- Study "burning" plasma and maintain for up to an hour



ITER



EU Fusion Roadmap – once again

- **European Fusion Roadmap**
  - Realization of fusion as energy source for electricity by 2050
    - ⇒ *Fusion Power Plant (FPP) providing electricity to the grid*
- **"Horizon 2020" research framework programme**
  - Conceptual design of a fusion power demonstration plant (DEMO)
  - **Power Plant Physics and Technology (PPPT)** programme conducted by **EUROfusion** Consortium for the Development of Fusion Energy
- **DEMO power plant**
  - Conceived as single step between ITER and commercial FPP
  - Demonstrate ***tritium*** *breeding capability, production of* ***net electricity****, all* ***technologies*** *required for the construction of commercial FPP*
- **D-Li neutron source IFMIF-DONES**
  - Provide material irradiation data required for the construction of DEMO

⇒ ***Implemented in PPPT projects including design activities & supporting R&D***

PPPT projects

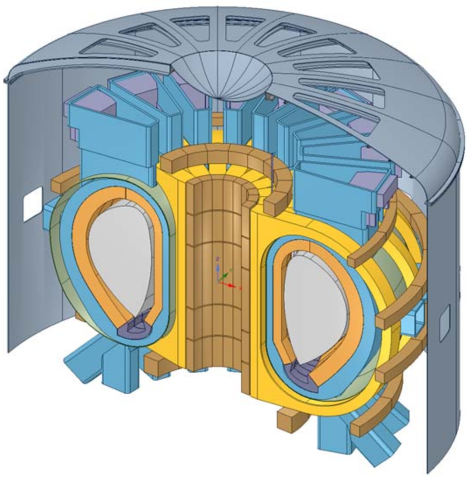
- **PMI –System Engineering, Design and Physics Integration**
- **BB – Breeder Blanket**
- **SAE – Safety and Environment**
- **MAT – Materials**
- DC – Diagnostic and Control
- DIV – Divertor
- RM – Remote Handling
- **ENS – Early Neutron Source ("IFMIF – DONES")**
- S2 – Stellarator Engineering

Neutronics serves all these projects:

⇒ ***Provides data required for nuclear design of plant, systems & components***

⇒ ***Evaluate & proof nuclear performance incl. licensing & safety related issues***

DEMO 2015 Baseline



CAD Configuration Management Model

"EU DEMO1 2015"

Main reactor parameters	
No. of TF coils	18
Major radius [m]	9.072
Minor radius [m]	2.927
Aspect ratio	3.1
Plasma elongation, κ_{95}	1.59
Plasma triangularitry, δ_{95}	0.33
Average neutron wall loading [MW/m^2]	1.05
Fusion power [MW]	2037
Net electric power [MW]	500

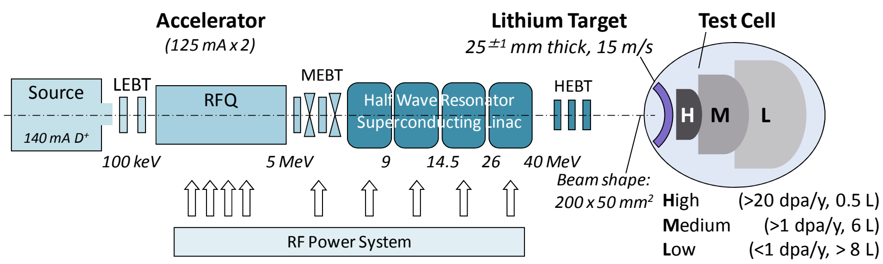
⇒ *New DEMO design underway !*

Neutronics - Issues & nuclear responses

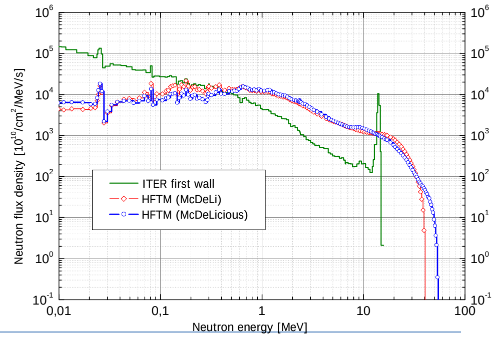
- **Tritium breeding capability**
  - Tritium Breeding Ratio (TBR); net TBR ≥ 1.0
    ⇒ *To be evaluated, optimized and proven*
- **Nuclear power generation**
  - Total power produced in nuclear reactions, spatial distributions
    ⇒ *Reponses to be provided*
- **Shielding performance**
  - Radiation loads to superconducting magnets, structural and sensitive components/elements
    ⇒ *To be evaluated, optimized and proven*
- **Irradiation effects: Activation, transmutation, decay radiation**
  - Activity & nuclide inventories, decay heat, radiation damage to materials/components, radiation doses to materials & personnel
    ⇒ *To be evaluated & minimized – for operation, maintenance, safety, decommissioning and waste management*

⇒ ***Suitable computational approaches, tools and data needed to provide the required response data with sufficient accuracy.***

IFMIF Intense Neutron Source



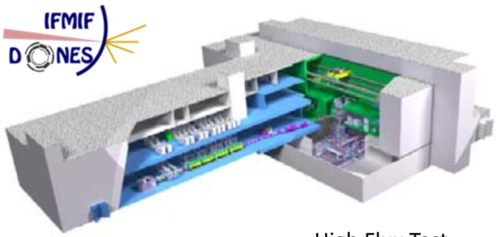
- Deuteron beams:
  - 2 x 125 mA
  - E_d = 40 MeV
- Neutron production:
  - ≈ 1.1 × 10^{17} s^{-1}
  - *Max. neutron flux density (at back plate): 1.2 × 10^{15} $cm^{-2}s^{-1}$*



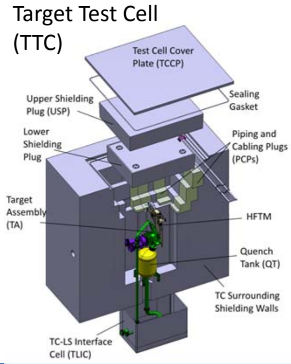
IFMIF-DONES Neutron Source

Demo Oriented Neutron Source

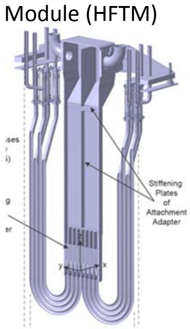
- Utilizes one full IFMIF accelerator with a deuteron beam (125 mA, 40 MeV) producing half the neutron intensity of IFMIF.
- Allows upgrading DONES at a later stage to the full IFMIF performance with a second accelerator.
- Lithium target, Test Cell and HFTM of DONES and IFMIF are identical while other irradiation modules are not considered in DONES.
- No hot cell, no Post Irradiation Examination (PIE) facility



Target Test Cell (TTC)



High Flux Test Module (HFTM)



IFMIF-DONES Neutron Source

Major neutronics issues/tasks

- D-Li neutron source producing neutrons up to 55 MeV – McDeLicious approach
- Nuclear performance of HFTM irradiation module
  - *Neutron/photon flux distribution & spectra*
  - *Nuclear heating in HFTM container & specimens (Eurofer steel)*
  - *Radiation damage & gas production in specimens*
- Target & Test Cell
  - *Nuclear design of Li target assembly, Li loop with quench tank, Test Cell with steel liner, concrete walls & plugs*
  - *Issues: nuclear heating (cooling), activation, radiation doses in/around TTC & Li loop during operation & maintenance ⇒ radiation maps*
- Accelerator Facility (AF)
  - *Radiation during operation due to deuteron beam losses and subsequent activation of AF components ⇒ deuteron transport (MCUNED code) & interaction with AF materials (activation, neutron generation)*
  - *Back streaming neutron radiation, shield design & optimization, beam dump*

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Addendum:

– DEMO nuclear analyses - examples

Neutronics simulations in Fusion Technology

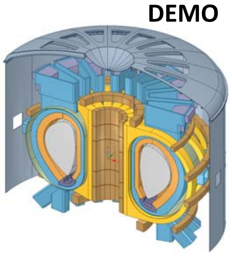
- **Neutron (and photon) transport simulations**
  - Basis for providing all **nuclear responses** needed for the design and performance evaluation of FT facilities.
  - Suitable computational approaches, tools and data required:
    - Method/tool for simulation of neutron transport in complex 3D geometry
    ⇒ *Monte Carlo (MC) particle transport technique (MCNP, TRIPOLI, etc.)*
    - **Nuclear cross-section data** to describe the nuclear interaction processes
- **Coupled activation and radiation transport calculations**
  - Basis for assessment of activity inventories and radiation fields after shut-down as required for safety, licensing, waste management
  - Computational approaches/tools and required:
    - Nuclide inventory calculation with coupling to particle transport
    - Large amount of neutron induced **activation cross-section data**

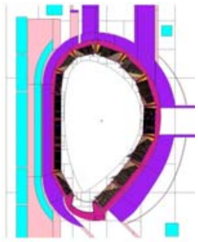
⇒ ***Neutronics simulations rely on variety and multitude of nuclear cross-section data ("nuclear data") - and their quality !***

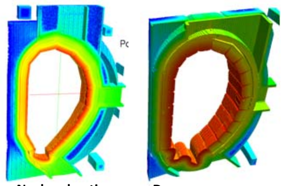
Neutronics Simulation Approach in FT

Facility design → Neutronics simulation → Nuclear responses

DEMO



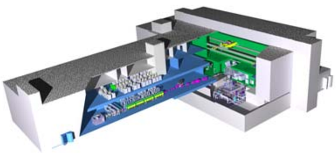


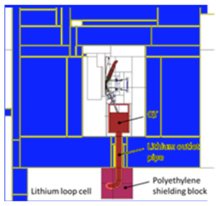


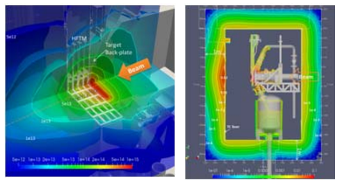
Nuclear heating   Decay gamma source

Tritium breeding, nuclear heating, activation & transmutation, radiation doses, …

IFMIF-DONES neutron source







Neutron flux   Nuclear heating

Displacement damage, gas production, nuclear heating, radiation doses, …

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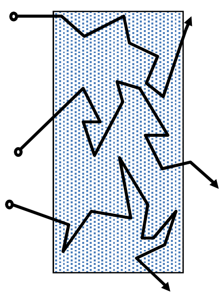
Faithful neutronics calculations

- Suitable method for simulation of neutron transport in complex 3D geometries
- High quality nuclear cross-section data to describe the nuclear interaction processes
- Simulation models which replicate the real geometry without severe restrictions

⇒ ***Fulfilled by Monte Carlo (MC) particle transport technique***

- *Can handle any complex geometry with high fidelity and sufficient detail*
- *Can employ nuclear cross-section data without severe approximations*
- *Can be coupled with nuclide inventory codes for coupled radiation transport and activation calculations*



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Faithful neutronics calculations for DEMO

- Reliability of employed MC particle transport code and its coupling to nuclide inventory calculations
  - To be validated with fusion relevant benchmark experiments

  ⇒ ***PPPT projects BB and SAE: R&D tasks on MC code TRIPOLI and European code system for coupled transport and activation calculations***
- Capability to describe in the simulation real reactor geometry with high fidelity and sufficient detail

  ⇒ ***PPPT project BB: R&D task on CAD to MC conversion tool McCad***
- Quality of nuclear cross-section data for fusion applications
  - To be checked against integral experiments

  ⇒ ***Development and qualification of nuclear data relevant to DEMO and ENS; tasks implemented in PPPT projects PMI, BB, SAE, MAT and ENS***

  ⇒ ***To be supported by experimental programme, planned for implementation in PPPT programme in 2019***

MC codes and related R&D in PPPT

- **MCNP-5, -6**
  - Developed by Los Alamos National Laboratory (LANL), USA
  - Very powerful and versatile, well validated and benchmarked, user friendly, most suitable for fusion applications
  - Standard MC code for ITER nuclear analyses, also used in PPPT

  ⇒ *Not freely available, subject to US export control regulations*

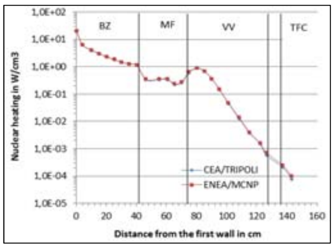
  ⇒ *Alternative MC codes considered in previous exercise on suitability for fusion neutronics, in particular DEMO nuclear analyses, including e. g. open source codes SERPENT, GEANT, and …*
- **TRIPOLI-4**
  - Developed by CEA Saclay, France, mainly for fission and shielding
  - Mature MC code, well advanced in its functionalities, validated for fusion neutronics and benchmarked against MCNP for DEMO application

  ⇒ *Accepted as analysis code for PPPT neutronics; selected as suitable candidate for further development within PPPT*

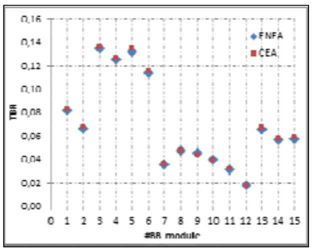
TRIPOLI-4 MC code

- Benchmarking against MCNP for DEMO application
- “DEMO 2014” with “Helium Cooled Lithium Lead” (HCLL) blanket

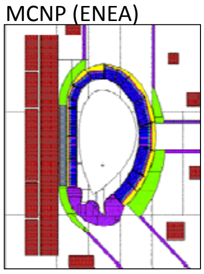
Nuclear heating profile



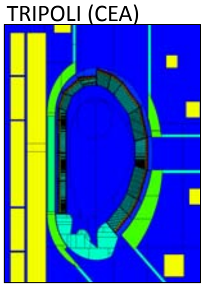
Tritium breeding in modules



MCNP (ENEA)



TRIPOLI (CEA)



⇒ *Agreement mostly within statistical uncertainties*

- Current R&D work on TRIPOLI within PPPT:
  - *Coupling to activation calculation scheme using CEA depletion code MENDEL*
  - *Nuclear data uncertainties propagation*

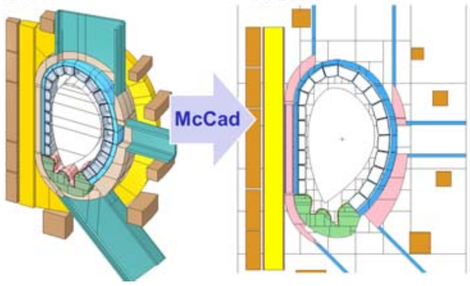
McCad geometry conversion tool

- **Software too**l for automatic conversion of CAD data into geometry representation of Monte Carlo codes, developed by KIT
- **Key features**
  - Based entirely on **Open Source Software** running under **Linux and Windows** Operating System, coded in C++
  - Use of **OpenCascade CAD kernel** for geometry operations, Qt4 libraries for Graphical User Interface (GUI)
  - Automatic generation of input decks for **MCNP** and **Tripoli**
  - Algorithms for conversion, void completion, model analysis, error check and user operations
  - Restricted to analytical surfaces (planes, cylinders, cones, spheres, etc.
- **Recent developments**
  - Improved decomposition algorithms, and functions
  - Integrated to SALOME platform including capability for generation of mesh models and hybrid geometries for MCNP6
  - Source code and binaries (Linux and Windows) freely available on github: https://github.com/McCadKIT/McCad

CAD to MC geometry conversion

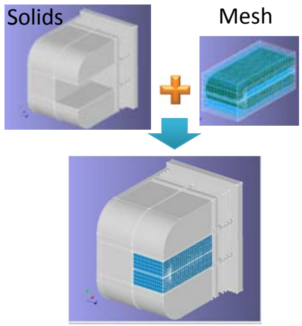
- Preparation on CAD platform (CATIA, SpaceClaim, ...)
  - *Fixing of geometry errors (gaps, overlaps, etc.,)*
  - *Removal of unnecessary small details*
  - *Replacement of surfaces described by spline functions*
  - *If required, pre-decomposition of complex models*
- Conversion + addition of void spaces (automated)

Conversion of DEMO 2014 CAD geometry model



McCad

Hybrid geometry approach



Solids + mesh combined

⇒ *Suitable for use with MCNP6*

Coupled radiation transport and activation calculation schemes

- Required for calculations of activation, decay heat and radiation fields post-irradiation (shut-down dose rates, SDR)
- Two approaches:
  - Direct 2-Step approach ("R2S") developed by KIT, CCFE & UNED by coupling of MCNP transport calculations (neutrons, decay photons) and FISPACT/ACAB nuclide inventory calculations.
  - Direct 1-Step approximation method ("D1S") developed by ENEA & IO assuming prompt photons can be replaced by decay gammas in MCNP transport calculation.

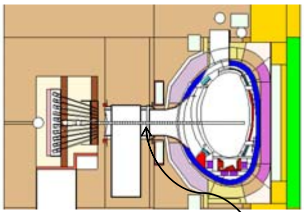
    ⇒ *No inventory calculations required, just one single MC transport calculation.*

⇒ *R&D task in PPPT project SAE on development of joint European R2S code system ("cR2S") from scratch.*

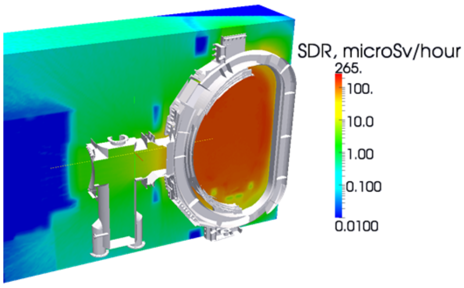
⇒ *Further development of D1S system for application to DEMO*

R2S/D1S validation on JET

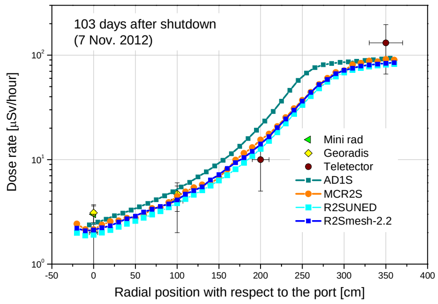
Available R2S code systems (CCFE, KIT, UNED) and D1S (ENEA) validated on 14 MeV neutron generator experiments and JET.



Shut-down dose rate distribution (one week after August 2012 JET shut-down) overlaid to the Octant 1 CAD geometry model



Shut-down dose rate profiles along horizontal mid-plane port (Octant 1): Calculation results vs. measured dose rates



⇒ ***Agreement mostly within ± 30%***

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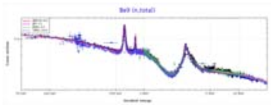
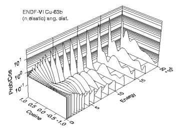
Nuclear data for FT applications

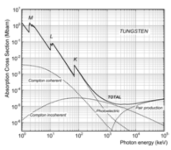
- **Neutron cross-sections for transport simulations**



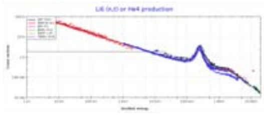
  - Neutron absorption and total cross-sections: $\sigma_a(E)$, $\sigma_{tot}(E)$
  - Total neutron emission cross-section $\sigma_{nem}(E,E',\mu)$
    [E = neutron energy, μ=cos(θ), θ=scattering angle]



    ⇒ *Includes elastic scattering and inelastic reactions (n,n'γ), (n,2n),..*
- **Cross-sections for photon transport simulations**



  - Neutron induced γ - production cross-sections and spectra
  - γ - interaction cross-sections
- **Nuclear data for calculating reaction rates ("nuclear responses")**
  - Cross-sections $\sigma_x(E)$ for specific reactions (tritium, gas production, etc.), and energy deposition (heating)



⇒ *Complete data evaluations required : all reactions, all data types, covering the entire energy range 10^{-3}eV – 20 MeV, for all nuclides of interest to FNT, sufficient quality (!)*

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Nuclear data for FT applications

- **Nuclear data evaluations & libraries**
  - Evaluated nuclear cross-section data compiled in libraries, processed for application calculations, benchmarked and validated – as far as possible.
- **Nuclear data libraries for fusion technology**
  - **FENDL - Fusion Evaluated Nuclear Data Library**
    - Developed under auspices of IAEA, tailored to the needs of ITER
    - Current version FENDL-3.1c includes a set of sub-libraries, (n, p, d, activation, co-variances, etc.), up to 200 MeV
  - **JEFF - Joint Evaluated Fusion and Fission File**
    - Organised and maintained by NEA Data Bank, Paris, addressing needs of European nuclear fusion and fission communities
    - EU fusion data evaluations are fed into JEFF and its sub-libraries

  ⇒ ***JEFF serves as reference data library for PPPT nuclear analyses***

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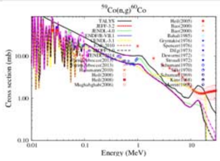
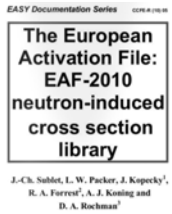
Nuclear data for FT applications

- **Activation cross-section data**
  - Excitation function σ_x (E) for any open reaction channel producing a radioactive product nuclide
  - Calculated by nuclear model codes using experimental data, benchmarked and validated for important reactions
  - **European Activation File (EAF)** developed by CCFE/NRG in the frame of EU fusion programme, **serving both JEFF and FENDL**
  - **EAF- 2010** latest version (frozen): 816 target nuclides ^{1}H to ^{257}Fm, 66,256 excitation functions up to 60 MeV.

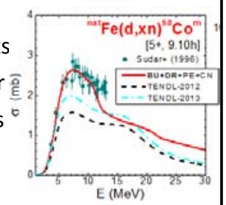



EASY Documentation Series

The European Activation File: EAF-2010 neutron-induced cross section library

J.-Ch. Sublet, L. W. Packer, J. Kopecky, R. A. Forrest, A. J. Koning and D. A. Rochman

- **Deuteron induced cross-section data**
  - Required for IFMIF-DONES nuclear analyses
    - Neutron generation in Li target and accelerator components
    - Activation of deuteron beam facing materials of accelerator
  - TENDL deuteron library, based on automated model calculations



⇒ *To be updated with specific data evaluations/improvements*

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General Purpose Nuclear Data Evaluations

Evaluations performed previous within fusion programme (F4E nuclear data grants/partnership agreement)

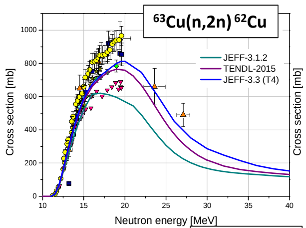
- **n + ^{181}Ta, ^{55}Mn, ^{63,65}Cu, $^{54, 56, 57, 58}$Fe, $^{90, -91,- 92,-94, -96}$Zr**
- Evaluations by JSI, KIT & TUW applying **Bayesian approach** taking into account experimental and model uncertainties.
- Nuclear model calculations largely based on **TALYS code** (NRG) and different approaches for the generation of co-variance data.
- Data files include all information/data required for FT applications (transport simulation, nuclear responses, uncertainties).

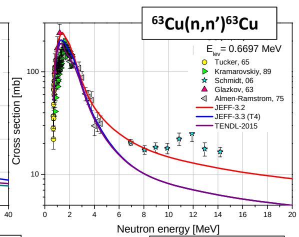
Evaluation activities implemented in PPPT, running in 2017 and planned for 2018 & later $\Rightarrow$ JEFF-4

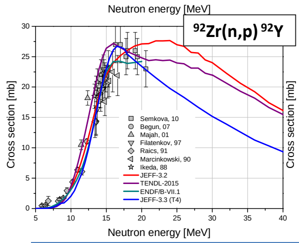
- Adaptive R-matrix approach for cross-section evaluations of light mass nuclei (TUW)
  - *Trial application to **n + ^{16}O** incl. production of prototype ENDF data file*
  - *Plans for application to new evaluation of **n + ^{9}Be** (2019/20)*
- New evaluation of W neutron cross-section data based on TALYS model calculations
  - *Evaluation of **n + ^{184}W** incl. co-variance data based on UMC approach (2017)*
  - *Evaluations for **n + $^{182, 186}$W** planned for 2018*

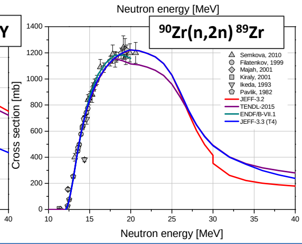
Evaluated Neutron Cross-Section Data - Examples

- *Nuclear model calculations with TALYS and adjusted parameters*
- *Geometry dependent hybrid (GDH) model for pre-equilibrium reactions*
- *Unified Monte Carlo (UMC) approach for co-variance data generation*

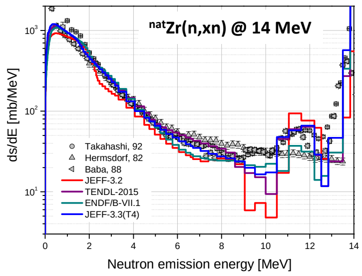


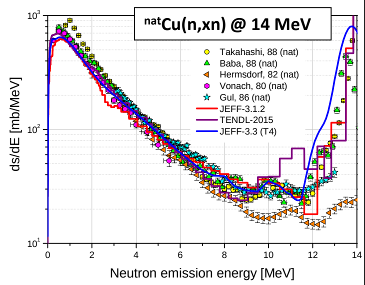






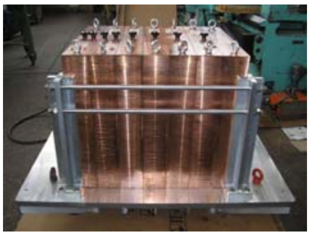
Neutron emission cross-sections



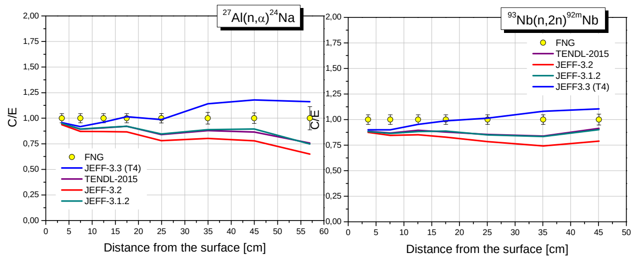


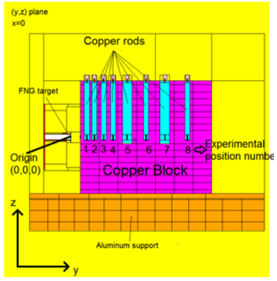
Benchmarking of Neutron Cross-Section Data - Cu

- **Integral experiments** essential for checking quality of nuclear cross-sections in transport simulations
- Irradiation of large material assembly by 14 MeV neutrons (FNG - Frascati Neutron Generator)
- **Cu benchmark experiment:**
  - *Copper block of 60 cm x 70 cm x 60 cm*
  - *Measurements of reaction rates with Au, Nb, Ni, Al, In and W activation foils , and neutron and photon flux spectra*



Cu assembly at FNG laboratory



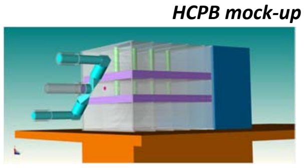


⇒ ***Revealed need to revise JEFF-3.2 Cu-evaluation for JEFF-3.3***

MCNP model (vertical cut)

Benchmark analyses on tritium breeding experiments

HCPB mock-up

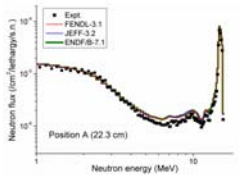


- Analyses of breeder blanket mock-up experiments to check status of state-of-the-art nuclear data libraries for prediction of tritium production
  - ⇒ *HCPB (Helium Cooled Pebble Bed) breeder blanket*
  - ⇒ *HCLL (Helium Cooled Lithium Lead) breeder blanket*
  - ⇒ *Experiments performed previously at FNG*
- Nuclear data libraries: JEFF-3.2, FENDL-3.1b, ENDF/B-VII.1

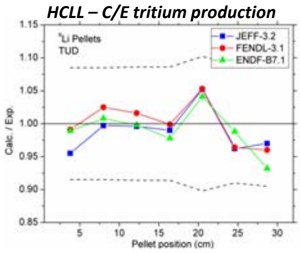
⇒ *All evaluations produce similar results*

⇒ *Tritium production well predicted for HCLL, underestimated for HCPB*

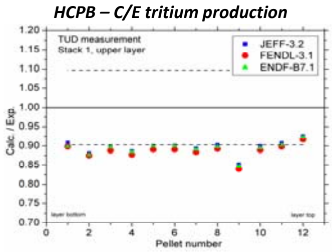
HCLL – neutron flux spectrum



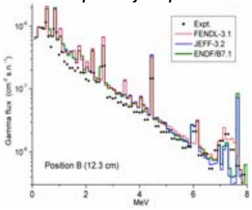
HCLL – C/E tritium production



HCPB – C/E tritium production



HCLL – photon flux spectrum



Activation Cross-Section Data Library

European Activation File (EAF):

- EAF series developed by CCFE/NRG in the frame of EU fusion programme, EAF-2010 latest version (frozen, no further development)

Strategy adopted in PPPT programme: Establish TENDL as reference data library for activation calculations

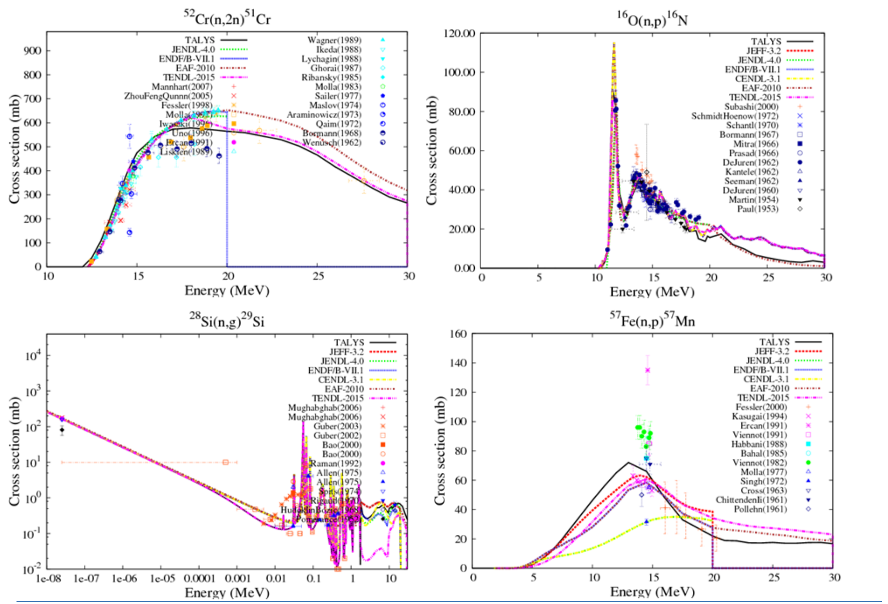
- TENDL - "TALYS based Evaluated Nuclear Data Library"
  - *Developed previously by NRG, now PSI, in collaboration with IAEA, CCFE, CEA and others*
  - *Very comprehensive and complete data library, largely based on automated TALYS calculations with default and adjusted parameters and data from other source*
  - *Includes cross-section data for n, p, d, t, ^{3}He, α and γ induced nuclear reactions*

⇒ TENDL to preserve or increase quality of EAF-2010 for activation calculations by including validated cross-sections and removing g deficiencies

- Deficient cross-sections identified and prioritised according to needs of fusion programme (DEMO, IFMIF-DONES, ITER) improved (N. Dzysiuk, NRG) and included in TENDL-2017 (D. Rochman, PSI)

⇒ *Generation of dedicated Activation Data File ("EAF format") from TENDL-2017, to be adopted as reference data library for activation calculations in PPPT programme, superseding EAF-2010*

Improved Activation Cross-Sections in TENDL



Gas Production Data Library

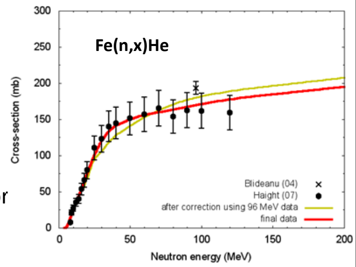
Gas production is an important issue for material performance during irradiation !

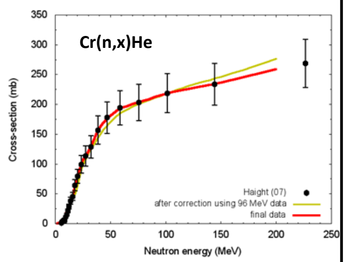
⇒ Gas production / damage ratio for specimens irradiated in IFMIF-DONES must match DEMO conditions

Available gas production data library

- Systematically evaluated gas production cross-section for nuclides Z=12 to 83 up to 200 MeV neutron energy (A. Konobeev, KIT)
  - *Based on experimental data, evaluated data, nuclear model calculations and systematics, and statistical combination of experimental and theoretical data*
  - *Includes production of protons, deuterons, tritons, ^{3}He, and α-particles in neutron induced reactions on 262 stable nuclides*

Available at:
https://www.inr.kit.edu/img/gas_production_files.zip





Displacement damage cross-section data

- **Displacement damage estimation**

Neutron flux density — PKA formation cross-section — Defect production — Displacement cross-section

$$\text{dpa/s} = \int \sigma_D(E)\cdot\Phi(E)dE = \int \Phi(E)\int_{T_{min}}^{T_{max}} \sigma_{PKA}(E,T)N_d(T)dTdE$$

NRT damage model

$$N_d(T) = \begin{cases} 0 & ;0 \le E_{dam} < E_d \\ 1 & ;E_d \le E_{dam} < 2.5E_d \\ \kappa\frac{E_{dam}}{2E_d} & ;2.5E_d \le E_{dam} \end{cases}$$

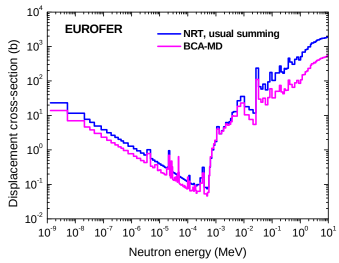
  - σ_d (E) for calculation of displacement damage (dpa/s) induced by incident neutron through transfer of kinetic energy to colliding nucleus
  - In general, use of (simple) **NRT damage model** to calculate number of lattice defects, recoil distributions from evaluated nuclear data files
  - **Advanced methodologies** based e. g. on molecular dynamics (MD) simulations or "athermal recombination corrected" (arc) dpa formalism

- **Available DPA data**
  - Complete data libraries based on JEFF-3.2 (NRT) and JEF-3.3 (NRT + arc-dpa)
  - Dedicated dpa cross-sections for Eurofer and SS-316, reference for PPPT

Displacement Damage Cross-Section Data

- **Advanced DPA cross-section data** up to 150 MeV for Eurofer constituents (Fe, Cr, Mn, V, W, Ta, C, Si, and N) based on an atomistic modelling approach.
- Molecular Dynamics (MD) and Binary Collision Approximation (BCA) model simulations for the calculation of number of lattice defects

⇒ *Better agreement with experimental point defect production data*.



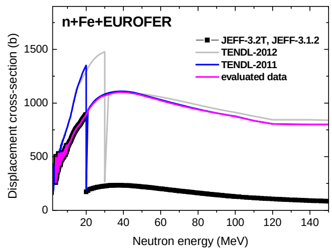
- Displacement damage cross-sections of Eurofer and SS-316 e available through IAEA/NDS:

  Eurofer: https://www-nds.iaea.org/public/download-endf/DXS/EUROFER_dpa-XS/ACE

  SS-316: https://www-nds.iaea.org/public/download-endf/DXS/SS-316_dpa-XS/ACE/

⇒ ***Provided as ACE data files for use with MCNP as dosimetry cross-sections***

⇒ ***Recommended for use in PPPT neutronics ("Guidelines for for Neutronic Analyses")***

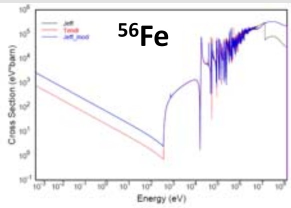


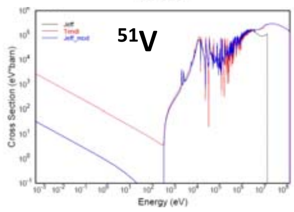
Displacement Damage Cross-Section Data Library

- Complete **DPA (NRT) cross-section data library** up to 150 MeV for 53 elements (171 nuclides)
- Based on processing of **JEFF-3.2** data with suitable extensions/corrections based on TENDL-2015

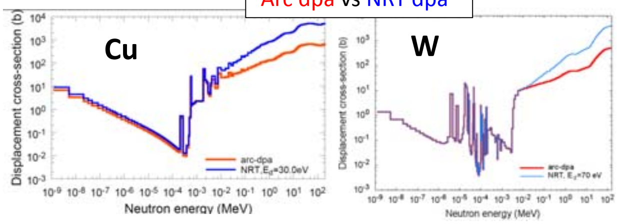
New approach adopted in running PPPT programme :

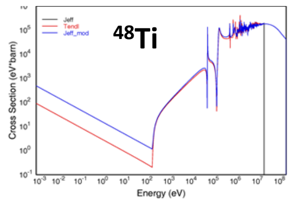
- **Arc dpa**(*) data which take into account lattice defects surviving thermal annealing
- Data library produced for elements Li to U based on cross-section data from **JEFF-3.3**.
- **Available at NEA DB as sub-library to JEFF-3.3 (Nov. 2017)**





Arc dpa vs NRT dpa



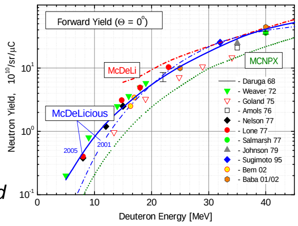


(*) *K. Nordlund et al., NEA/NSC/DOC(2015)9, OECD 2015*

Deuteron Induced Cross-Section Data

Required for IFMIF-DONES neutron source facility – ENS (Early Neutron Source) project in PPPT programme

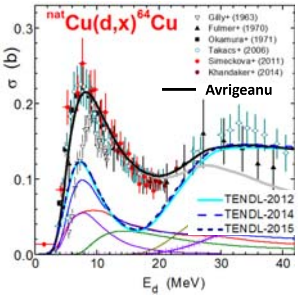
– Neutron generation in Li target: ^{6,7}Li(d, xn) cross-section data provided with McDeLicious MC code, validated with measured thin and thick target yield data



– Deuteron cross – section data for <u>activation</u> calculations:

⇒ *Available with TENDL data library, largely based on automated TALYS calculations with default model and parameters lacking sufficient accuracy*

⇒ ***Dedicated effort in PPPT programme to improve nuclear models describing deuteron induced reaction mechanisms***



– Deuteron cross – section data for <u>transport</u> simulations:

⇒ *Available with the same TENDL deuteron data library*

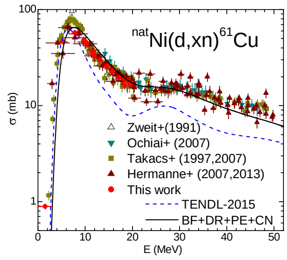
⇒ *Can be used in deuteron transport simulations with MC code code MCUNED (P. Sauvan, UNED)*

⇒ *In general, poor data quality because of deficient reaction models in TALYS, to be improved !*

Deuteron Induced Cross-Section Data

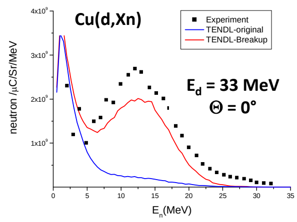
- d-induced <u>activation</u> cross-sections available for ^{27}Al, ^{54,56,57,58}Fe, ^{58,60,61,62,64}Ni, ^{63,65}Cu, and ^{93}Nb up to 60 MeV deuteron energy with improved nuclear models (M. Avrigeanu, IFIN-HH)

⇒ *Improved activation cross-sections to be included in new TENDL deuteron data library, extension to other nuclides*



- Deuteron <u>transport</u> : Parameterised representation of deuteron break-up implemented MCUNED code (P. Sauvan, UNED)
- Successfully tested with ad-hoc modified TENDL deuteron data library

⇒ *Data for transport simulations to be improved in TENDL*



Planned activities in PPPT (2018 and later) ⇒ JEFF-4

– *Improved modelling of d induced reactions in TALYS code*

– *Updated versions of TENDL deuteron library for transport and activation simulations*

Summary

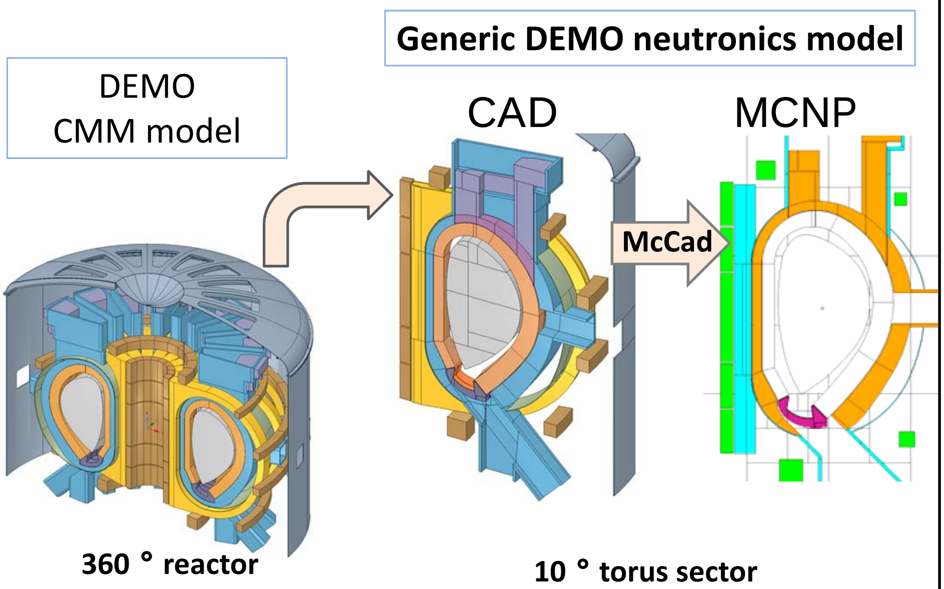
- Nuclear data for fusion technology
  - *High quality data essential for design optimization, performance evaluation; safety, maintenance and waste management*
  - ⇒ *Pre-requisite to ensure reliable analyses and results*
- Requires dedicated development efforts
  - Tailored to PPPT project needs: DEMO, IFMIF-DONES
  - ⇒ *Nuclear data for transport simulations – neutrons, deuterons*
  - ⇒ *Activation cross-section data - neutrons, deuterons*
  - ⇒ *Special purpose data, e. g. displacement damage, gas production*
- Requires benchmarking against integral experiments
  - *Neutron transport/shielding, breeding, activation*
  - ⇒ *To be conducted within PPPT programme according to project needs*

- What is fusion ?
- EU fusion roadmap
- Neutronics simulations in fusion technology
- Nuclear data for fusion applications
- Nuclear data in the PPPT programme
- Summary

Addendum:

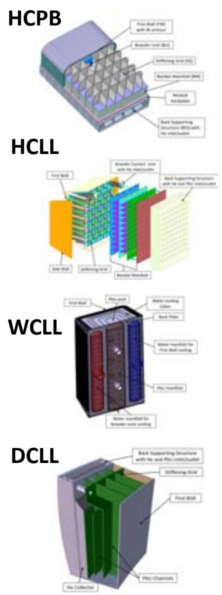
– **DEMO nuclear analyses - examples**

DEMO Model Development (2015)



Breeder Blanket Design

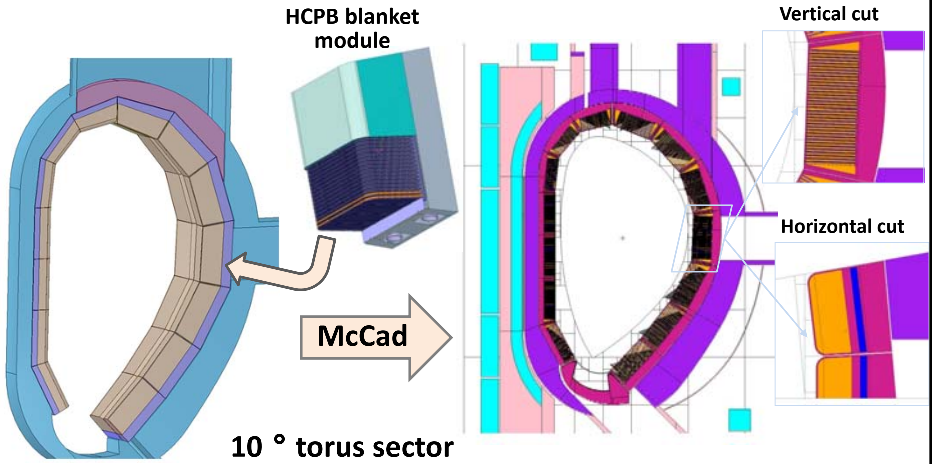
- **Breeder blanket concepts considered in PPPT for DEMO:**
  - *Helium Cooled Pebble Bed (**HCPB**) blanket, Beryllium as neutron multiplier and He gas as coolant,*
  - *Helium Cooled Lithium Lead (**HCLL**), PbLi breeder and He gas as coolant,*
  - *Water Cooled Lithium Lead (**WCLL**), PbLi as breeder and water as coolant,*
  - *the Dual Coolant Lithium Lead (**DCLL**), PbLi as breeder and coolant, and He gas as coolant for the structure.*
- **Required nuclear analyses:**
  - Design optimisation & evaluation (TBR, shielding)
  - Nuclear heating for thermal-hydraulic layout
  - Activation, afterheat for safety and waste management



HCPB DEMO Model (2015)

CAD neutronics model
with blanket module segmentation

MCNP model



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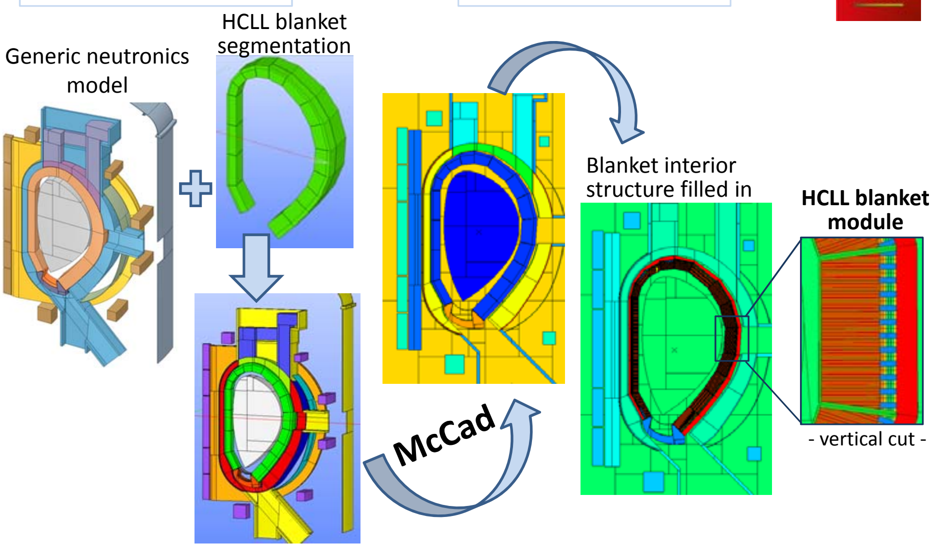
HCLL DEMO Model (2015)

CAD model

TRIPOLI model



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Tritium breeding potential

- DEMO requires **Tritium self-sufficiency:**

  ⇒ *Net Tritium Breeding Ratio (TBR) > 1.0*

- **DEMO design target:** TBR ≥ 1.10

  (To be proven by 3D Monte Carlo calculation without blanket ports).

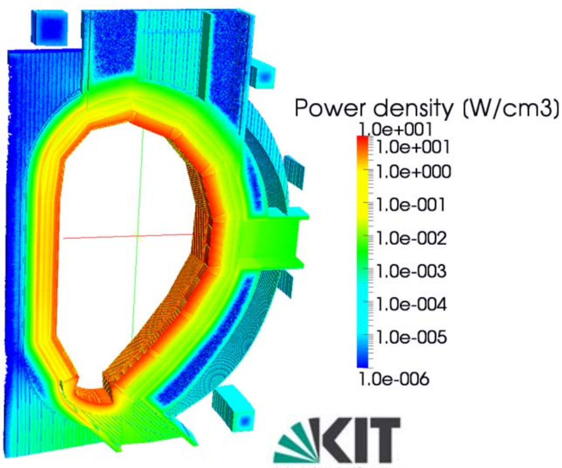
Blanket	TBR (reference design)	TBR (design variations)	Remarks
HCPB	1.20	1.17 – 1.37	DEMO 2015 baseline, a variety of design variations considered
HCLL	1.15	1.15 – 1.22	DEMO 2015 baseline, some design variations considered
DCLL	1.10	-	*DEMO 2014 baseline*
WCLL	1.13	-	*DEMO 2015 baseline with homogeneous breeder mixture*

⇒ ***All blanket concepts show sufficient tritium breeding capability for DEMO***

Nuclear power generation in DEMO

HCPB DEMO

3D distribution of power density



DEMO 2015

Fusion neutron power: 1630 MW

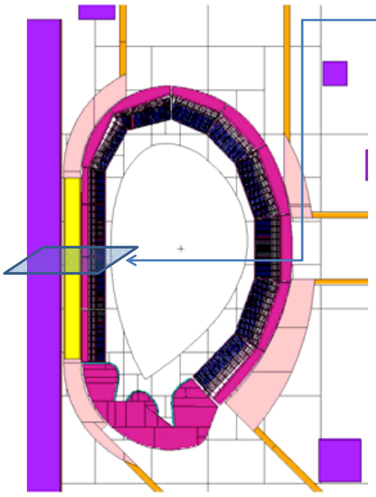
⇒ ***Energy multiplication*** *through nuclear reactions*

	Energy multiplication M_E
HCPB	1.35
HCLL	1.199
DCLL	1.198
WCLL	1.20

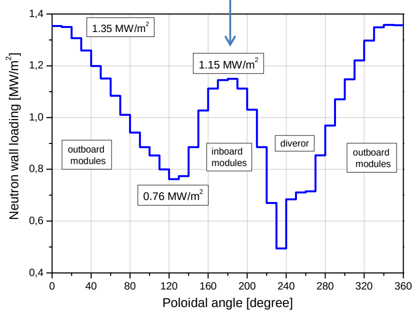
Power release fraction	
Blanket modules	≅ 90 %
Divertor	5 – 6 %
VV/shield	balance

Shielding calculations

Shielding calculations in torus mid-plane (inboard)



Inboard mid-plane

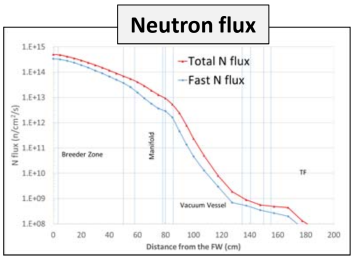


Poloidal distribution of Neutron Wall Loading (NWL) in DEMO 2014

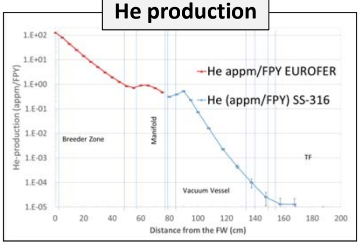
Shielding Performance of WCLL DEMO 2015

Radial profiles at DEMO inboard torus mid-plane

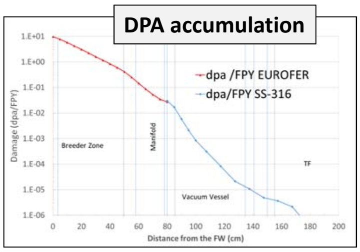
Neutron flux



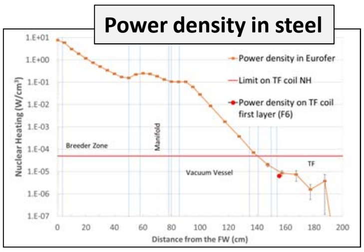
He production



DPA accumulation

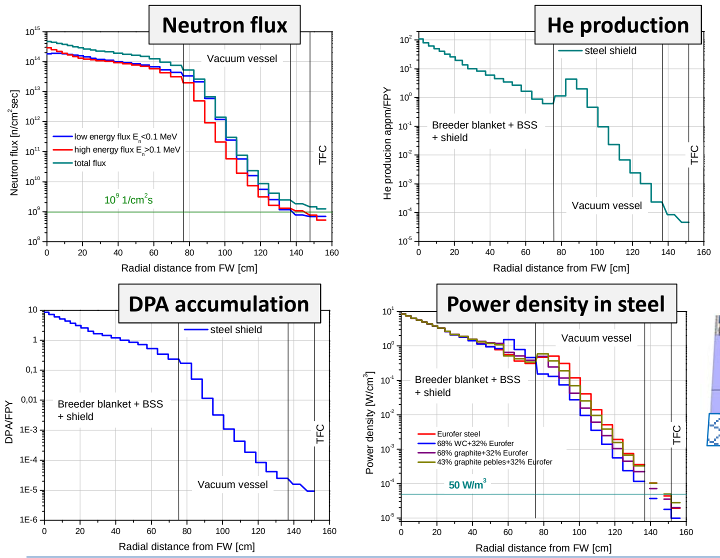


Power density in steel

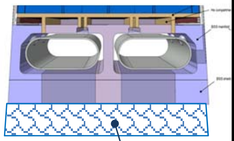


Shielding Performance of HCPB DEMO 2015

Radial profiles at DEMO inboard torus mid-plane



Blanket back support structure (BSS) with manifold

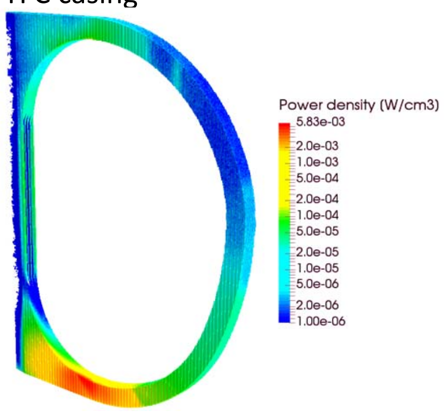


BSS shield options

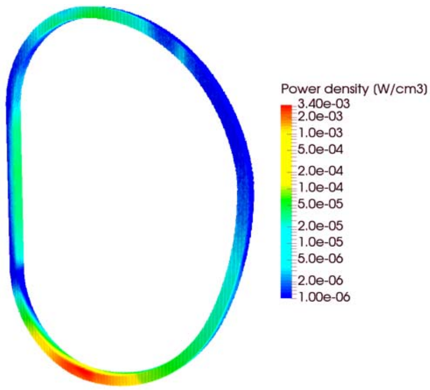
Nuclear power in TFC

3D distribution of power density

TFC casing



TFC magnet

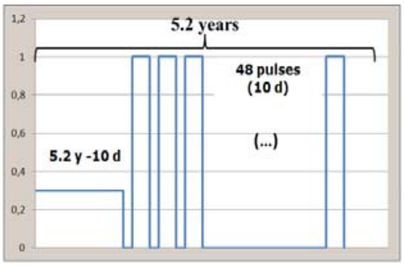


	Power release in one TFC	Power release in all TFCs
TFC casing	1.6 kW	29 kW
TFC magnet	620 W	11 kW

⇒ *Design limit of 50 W/m³ for TFC heating exceeded in divertor port area*

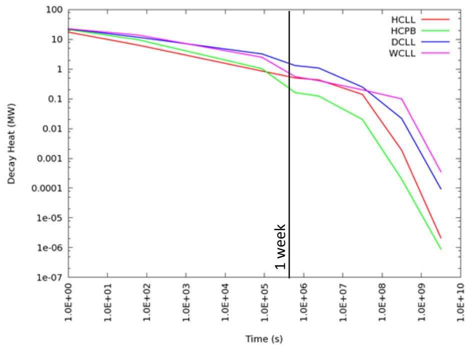
Activation and afterheat

Irradiation scheme



Decay heat of blanket modules [MW]

DEMO 20014 (1572 MW fusion power)



Decay heat power

- Typically 20 MW (≅ 1.5 %) @ 1s, ≅ 0.1 – 1 MW (≤ 0.1 %) @ 1 week after shut-down
- Dominated by activation of Eurofer steel
- Significant differences among blanket concepts only for longer decay times (≥ 1 week) ⇒ Neutron spectra effects

Vacuum vessel activation and decay heat

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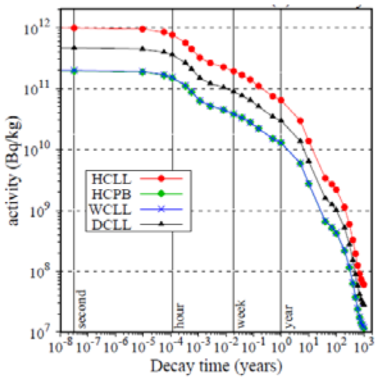
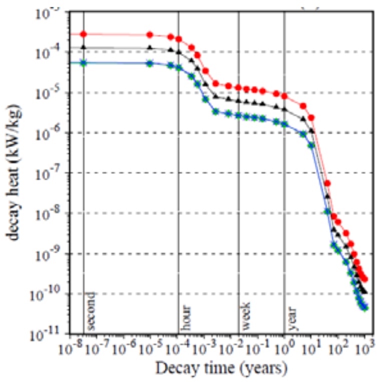
Specific activity [Bq/kg]



Decay heat density [kW/kg]



- Significant effect of blanket types (mixtures) on VV activation
- Highest VV activation for HCLL, lowest for HCPB and WCLL blanket mixtures

  ⇒ *Effect of neutron spectrum and flux attenuation across blanket modules*

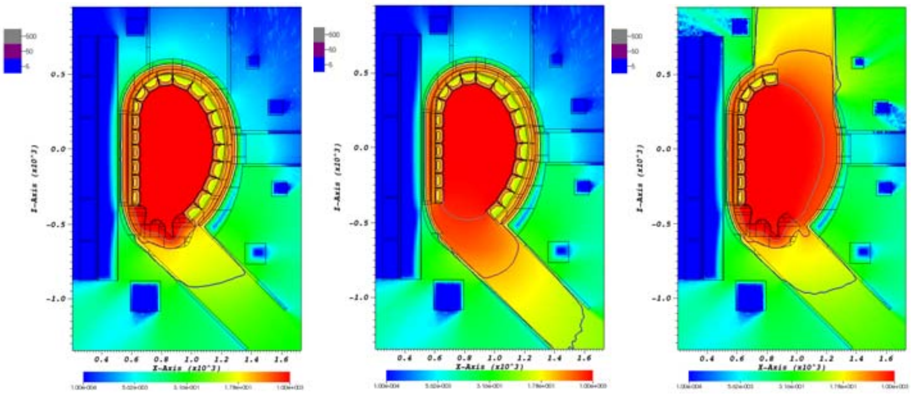
  ⇒ *Used for classification of radioactive waste*

Radiation fields during maintenance

3D distributions of biological dose rates [Sv/h], 4 weeks after DEMO shut-down

HCPB DEMO 2014

All irradiated components in place | **Divertor removed** | **Upper port shield and outboard blanket segment removed**



- Similarly, radiation doses to materials/sensitive components
  - ⇒ *Required for remote maintenance studies*

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